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Experimental study on the rate-dependency of reinforced concrete structures using slow and real-time hybrid simulations

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ABSTRACT

A great number of studies have been conducted to study the loading rate effect on the behavior of reinforced concrete (RC) structures. A majority of these studies, however, are focused on the component behavior of an RC specimen by imposing a predefined cyclic displacement history on the specimen without considering the interaction of the specimen with the entire structural system. In this study, the rate-dependency effect of an RC pier on the global response of a bridge is experimentally investigated using the slow and real-time hybrid simulations. The RC pier is used to support a two-span prestressed concrete girder bridge. The nonlinear response of the bridge under earthquake loads is accounted for by physically testing the RC pier in a laboratory, while the upper structural system of the bridge including the bridge deck and girders are analytically modeled. A dynamic servo-hydraulic actuator is connected to the top of the pier to transfer the inertial force of the bridge deck and girders to the pier. Due to the lack of knowledge in real-time force control, the axial load effect on the dynamic response of the RC pier is not considered in this study. Prior to conducting the hybrid simulations, predefined cyclic displacement tests are conducted for the bridge pier specimens with the same displacement history, but with different rates, in order to investigate any change in strength and energy dissipation capacity of the RC pier. Then, a series of slow and real-time hybrid simulations are conducted to investigate the rate-dependency effect on the seismic response of the bridge. The results from the predefined cyclic displacement tests and hybrid simulations are provided and discussed along with the observation from these tests.

1. Introduction

It is well-known that reinforced concrete (RC) structures have a rate-dependent behavior under various dynamic loadings. A number of studies have been conducted to investigate the effect of rate-dependency of RC structures on their dynamic response [1–12]. Generally accepted findings from these studies are that the strength and the energy dissipation capacity of RC structures are substantially increased under high strain rates. The enhancement in strength and energy dissipation can be beneficial to reduce the displacement response of concrete structures. In general, the enhancement is simply ignored since it can result in a conservative design compared to the typical design procedure for RC structures, which is based on *static* test results. However, researchers found that higher loading rates can change the failure mode of concrete structures, potentially leading to an unexpected failure of a structure under earthquake loadings. Mutsuyoshi and Machida [1] reported a shift from the flexural failure of RC beams at low loading rates to the shear failure at high loading rates. On the other hand, Kulkarni and Shah [2] observed a shift from the shear failure at low loading rates to the flexural failure at high loading rates for their RC beams. An increase in strength of RC structures under high loading rates can increase other force demand at critical points and possibly change the failure mechanisms of RC structures, which is not expected under static loading tests (i.e., low loading rates). This may reduce the actual lateral deformation capacity of RC structures under earthquake loads, raising concerns in seismic design for RC structures [3]. In addition, recent experimental studies showed that high loading rates can reduce the ductility factor of RC beams [4] and result in greater stiffness degradation at the RC beam-column joints during the post-yield response [5]. Therefore, considering the rate-dependency effect is very important to accurately understand the dynamic behavior of RC structures under earthquake loads. Furthermore, the rate-dependency effect on the *global* response of a structure needs to be studied. A majority of existing studies are focused on the individual behavior of an RC specimen by imposing a predefined cyclic displacement (or

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load) history on the specimen without considering the interaction of the specimen with the entire structural system. The global response of a structure can be significantly affected by the interactive response of the RC specimen with the entire structural system as well as the possible change in the failure mechanism due to a fast loading rate of earthquake loads.

Conducting a shake table test would be a good method for such a study. The rate-dependency of RC structures is automatically accounted for by having the shake table excited with the same acceleration time history as the earthquake ground motion. In that regard, recent shake table tests on RC bridge piers provided a better understanding of the actual seismic response of RC bridge piers [13,14]. However, the cost for shake table test is expensive, especially when a large-scale structural system is used, since it generally requires the construction of *entire* or *a large portion of* structural systems. Unlike the shake table test, hybrid simulation does not require a large experimental cost since it only involves a physical specimen of our interest (i.e., the experimental substructure), while the remaining structural components are analytically modeled (i.e., the analytical substructure). In hybrid simulation, the global structural response is obtained by combining the experimental and analytical substructures together, then solving the equations of motion numerically. If the hybrid simulation imposes a displacement or load on a specimen in a real-time manner, it is called a real-time hybrid simulation. Thus, the real-time hybrid simulation can effectively account for the rate-dependency issue at a relatively low cost, while the pseudo-dynamic test (i.e., slow hybrid simulation) cannot capture the rate-dependency characteristics of RC structures.

Recent advances in equipment and control algorithms for servo-hydraulic actuator systems enable large-scale real-time hybrid simulations to be conducted in a laboratory [15–20]. In particular, more recently developed actuator control algorithms can accurately impose the target displacement on a specimen even though the specimen has a highly nonlinear response as can be observed in a typical RC structure at a large displacement [21]. In this paper, the effect of rate-dependency on the dynamic response of a two-span bridge with a reinforced concrete pier in the middle is investigated by conducting slow and real-time hybrid simulations. The entire bridge except for the central pier is analytically modeled and the RC pier is physically tested in a laboratory. By conducting a real-time hybrid simulation, the rate-dependency of the RC pier is included in the simulation, and its effect on the seismic response of the bridge can be investigated by comparing the results with those from the slow hybrid simulation. Due to the lack of current knowledge in the real-time force control for axially stiff members, however, the axial load effect on the seismic response of the RC piers is not included in this study. It should be noted that this paper is more focused on the study of the rate-dependency effect on the *global* response of a structure by conducting slow and real-time hybrid simulations based on the currently available technology for implementing these hybrid simulations. Prior to conducting hybrid simulations, predefined cyclic displacement tests were conducted for the bridge pier specimens with the same displacement history, but with different rates, in order to investigate any change in strength and energy dissipation capacity depending on the velocity imposed on the RC specimen.

2. Selected bridge structure for hybrid simulations

Fig. 1 shows a typical two-span bridge of this study with prestressed concrete girders. A T-shape RC bridge pier is located in

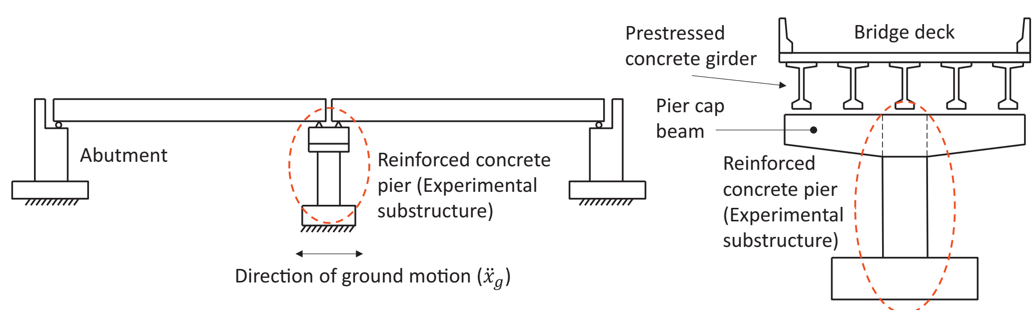
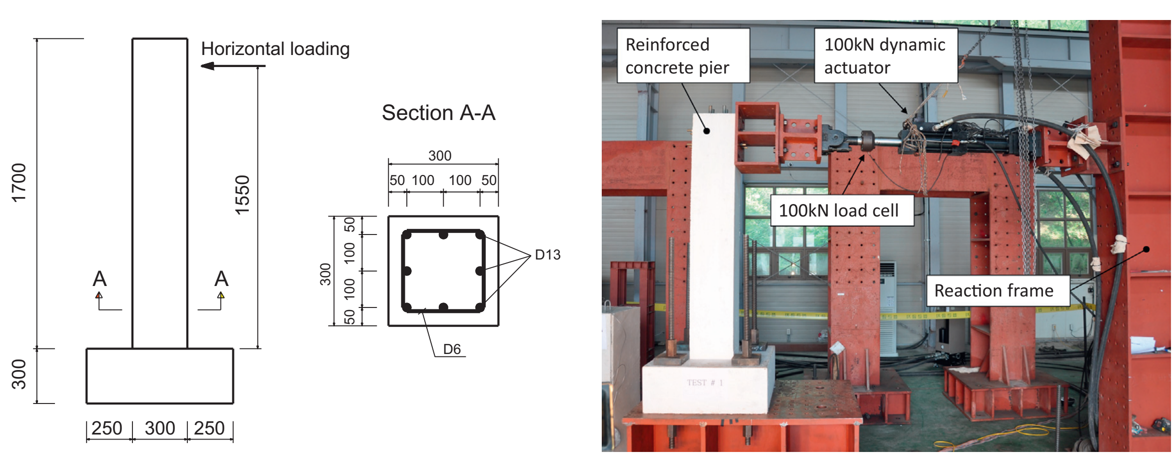


Fig. 1. A two-span prestressed concrete girder bridge.



(a) (b)

Fig. 2. (a) Drawing for reinforcement bars (unit: mm); (b) Experimental test setup.